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METALLIC REINFORCING MATERIAL AND METAL FIBER COMPOSITE MATERIALS

by

A. Wende

FOREIGN TECHNOLOGY DIVISION

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13. ABSTRACT

The physical properties and uses of plastics reinforced with quartz fibers, steel wires, glass fibers, boron fibers, and boron tungsten fibers are discussed. [AP1045701]

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Quartz						
Steel						
Glass Fiber						
Boron Fiber						
Tungsten						
Reinforced Material						
Composite Material						
Reinforced Plastic						

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METALLIC REINFORCING MATERIALS & METAL FIBER COMPOSITE MATERIALS

Translation of an article by A. Wende, in Plaste und Kautschuk, 1971, vol. 18, (1) pp 3-6.

Glass fibers predominate as reinforcing material for plastics. They are supplemented significantly by various other reinforcing materials such as inorganic and metallic fibers. A brief summary is presented, concerning properties and technical performance of reinforcing materials and of the reinforced plastics manufactured from them.

1. Reinforcement with fibrous metallic materials

1.1. Reinforcement with steel wire

Taprogge [1] used cold drawn steel wires with the properties indicated in Table 1, which were unidirectionally bonded onto a polyester mat. The individual layers contained 24 and 8 wires/cm. According to Jaray [2] it is possible to prepare laminates with 25 layers of steel wire/cm, in which a single layer contains 24 wires/cm. This corresponds, according to the equation:

$$\varphi = \frac{n z F_D}{b h}$$

(n number of wire layers
z number of fibers to a layer of width b
F_D wire cross section area [cm^2]
b width of a square sample [cm]
h height of a square sample [cm])

in a proportion of 29.5% by volume. The modulus of elasticity E_F of laminates that are unidirectionally reinforced with steel wire runs out almost linearly from the flexural stress/load deflection curve to rupture. The values for steel wire reinforced plastic deviate from the theoretical characteristic, because as a consequence of less adhesion than in the case of glass fibers, the resin can become detached from the steel wire. In Figs.1 and 2, according to [1], the modulus of elasticity in flexure and in tension, as well as the bending strength of laminates reinforced unidirectionally with steel wire are shown as a function of percentage of fiber volume content. Glass fiber reinforced laminates are introduced for the sake of comparison. Fig.3 shows the impact bending strength.

From the curves of Fig.1, it can be seen that the actual E-modulus of steel wire reinforced laminates drops as contrasted to theoretically obtained data, whereas the empirically introduced values are about twice those of GFP [glass fiber/polyester laminate?].

The low bending strength, ca 3500 kp/cm^2 in the case of UP [unsaturated polyester]-resins used as binder is attributable to the poor adhesion of the steel wire. If EP [epoxy]-resins are used, with the same volume proportion of fiber according to Fig.2, the bending strength rises to almost 6000 kp/cm^2. In the case of impact bending strength, there is clearly a maximum for the fiber volume component which has not as yet been worked out experimentally for steel wire. According to Fig.3, the curve for steel wire-EP resin might run similarly to that for glass yarn - UP resin.

The poorest adhesion according to [1] is for the combination UP-resin -steel wire (resistance to pulling out, average 18 kp/cm^2), while with epoxy resin as binder optimal strengths were attained.

According to [3] the strength of the laminate, with assumption of optimal adhesion, is determined solely by the number of wires. With 0.01 mm diameter (10 μm), strengths of about 10,000 kp/cm^2 were attained. The E-modulus of the composites, with about $0.75 \cdot 10^6$ kp/cm^2, is approximately double that of GFP.

The permanent strength of a steel wire is about 40% of its short time strength. Similar relationships obtain for the laminate, so that according to Fig.4, 30% of the short time strength ought to be permissible. Permanent cycle strengths of 3000 kp/cm^2 are reached, which is higher than in the case of GFP and solid steel.

Moisture reduces permanent strength to 22% so that permanently there is no longer any difference, according to Fig.5, between steel and wire laminate.

The combination of steel wire and glass is interesting. According to a report from the Batelle Institute [4] a continuous process has been developed for encasing a glass sheath with thin wires. With this method ultrafine wires are obtained, with diameters between 1 and 30 μm, and strength of 400 kp/mm^2.

1.1.1. <u>Fields of application of steel wire reinforced laminates</u>

Fields of application include, for example, pipe and containers. Hydrostatically stressed pipe made of this composite material fissures at approximately the theoretical value of 13 ... 14 kp/wire. Behavior in fissuring is like that of steel pipe, not like that of GFP pipe. The fissure begins limitedly: the destruction is not general.

Pipe and containers made of GFP thus far could only be used in dimensions with the limit value 160, for the product of diameter [cm] and pressure [kp/cm^2]. With steel wire reinforced composites, it is possible substantially to exceed this figure. Fundamentals are being determined at present for fittings and blind flanges, so that these structural parts can be dimensioned correctly. The use of distillation columns and other chemical apparatus is being tested. The basis for static calculation of parts that are reinforced with steel wire foil are available.

1.2. Reinforcement with boron-tungsten wires

If the E-moduli of various fiber materials are compared (Fig.6), it appears that fibers made of stainless steel yield only a medium value. In the plastic composite, with a fiber volume component of 50% steel wire, an E-modulus of maximally 10,000 kp/mm^2 is attainable. In contrast, with boron-tungsten wires there is an E-modulus of 25,000 kp/mm^2. According to [5] for an experimentally determined boron fiber component of 60.2 ... 61.4% and an E-modulus of the EP-resin of 320 kp/mm^2 there was for a unidirectional boron fiber plastic material according to the mixing rule, an E-modulus of 23,400 ... 25,900 kp/mm^2 which could be confirmed experimentally. Kochendörfer and Jahn [6] had similar results.

Because of lacking ductility and the glass-forming properties of boron, there are differences between ordinary wire drawing methods and the Taylor method. The only technological route to fiber production is via separation of boron from boron halides in the gaseous phase onto a heated tungsten wire. According to [7] these boron-tungsten wires have a wire diameter of about 100 μm whereby the diameter of the tungsten core is 16 μm and the density 2.7 g/cm^3. Experiments in replacing tungsten by less expensive quartz or carbon will be carried out. There is difficulty in production of continuous fibers, as attempted [5]. At present the maximum length is about 300 m.

In tension and bending rupture, there is almost always a lengthwise split observable, which points to nonhomogeneous distribution of internal stress. Also, technologically (fiber length) and chemically (growth conditions) there is need for improvement. A measure of the frequency of flaws in the fiber according to [6] is the decreasing average tension strength with increasing fiber sample length, as shown in Fig.7.

Boron-tungsten wires have a high heat stability in an inert gas atmosphere. With brief heating to 1100°C, according to [8,9] they have a drop in strength of only 20%. Above this temperature there is a rapid drop. Oxidation decomposition begins at temperatures $<$ 300°C as is shown in Fig.8.

1.2.1. Strength behavior of boron fiber reinforced plastic

The processing of boron fiber reinforced plastic, in the present state of the art, relates only to prepreg [preimpregnation process] semifinished goods with the filaments directed in parallel. Industrially, in the US boron fiber webs have been prepared which according to the information of Whittaker Co. contain 87 filaments/cm, to obtain an optimal fiber volume component of about 50% [6].

Ordinary epoxy resins are used as binder, and for thermally highly stressable laminates, polyimides and polyquinoxaline are used (Table 2).

Elasticity in tension and compression loading of plastics reinforced with boron fibers according to [5] is shown in Fig.9.

The E-modulus in compression is slightly higher, a phenomenon that is characteristic of boron fiber reinforcements.

Behavior in tension and compression is similar, see Fig.10.

In flexural strength and flexural rigidity experiments, the support-to-thickness ratio is significant for the 3-point flexural load, as indicated in Fig.11 according to [5]. Thereby a ratio of $l/d = 60$ is necessary.

Table 2 gives a survey of the strength properties of boron fiber composites with various binding agents according to [6].

1.3. Mixed laminates

By disposition of wires in the zone of tension of a GFP laminate, the bending strength and rigidity can be substantially increased. With steel wires, for instance, in the case of epoxy-resin-glass laminates, high bending strengths are also attained, while by addition of boron-tungsten wires the E-modulus in tension is about 30% higher than in steel wire reinforced laminates and mixed laminates (see Table 3). In mixed-reinforcement laminates, even with slight amounts of boron, high E-moduli can be attained. With 76% by volume resin and 13% by volume continuous glass filament mat and 11% by volume boron fibers, there is an E-modulus of $7.1 \cdot 10^5$ kp/cm^2 which is comparable to the E-modulus of pure continuous glass filament and aluminum.

1.4 Field of application for boron fiber reinforced plastic

The advantage of boron fiber reinforced plastic resides in the favorable relationship between density and strength. In [6], with reference to an example, the impressive structural weight reduction for a construction part with secondary structure is demonstrated with respect to high cost. However, all uses thus far have been limited to extreme light construction in air and space travel. The possibilities for building stringer profiles with boron fiber reinforced plastic is described in [6] in more detail by means of Fig.12.

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captions

Fig.1 E-modulus in flexure and tension, of unidirectionally reinforced laminates as a function of the fiber volume component

▲ quartz yarn + (1) Refer to p 8.
✖ steel wire + (2)
○ steel wire + (3)
◆ glass yarn + (4)
△ glass yarn + (5)
▭ quartz yarn + (6) (flat rod) (7)
● quartz yarn + (8)
○ glass yarn + (9) (round rod) (10)

Fig.2 Bending strength of unidirectionally reinforced laminates as a function of the fiber volume component

○ steel wire (1) Refer to p 8.
● steel wire (2)
△ glass yarn (3)
■ quartz yarn (4) (flat rod) (5)
✕ continuous spun glass filament (6)
▲ quartz yarn (7)
□ glass yarn (8) (round rod) (9)
◆ Scotchply 1002U (10)

Fig.3 Impact bending strength of unidirectionally reinforced laminates as a function of fiber volume component

■ steel wire (1) Refer to p 8.
□ steel wire (2)
◆ quartz yarn (3)
▲ glass yarn (4) (flat rod) (5)
✕ quartz yarn (6)
△ glass yarn (7)
○ continuous spun glass filaments (8) (round rod) (9)

Fig.4 Cycling stress (dry) in the case of steel wire laminates (a) and wires (b) Refer to p 8
a) stress
b) change of load

Fig.5. Cycling stress of various materials[strength is indicated in % of short time strength: a) wire and wire laminate (dry) b) wire laminate (wet) c) GFP (dry) d) GFP (wet)] Refer to p 8
a) strength
b) change of load

Table 1 Properties of steel wire in comparison to glass fibers Refer to p 9
a) reinforcing material (1)
b) type of reinforcement (2)
c) manufacturer (3)
d) fiber diameter (4)
e) fiber fineness (5)
f) density (6)
g) sizing (7)
h) fiber strength (8)
i) E modulus of fiber (9)
j) E glass [glass filaments made of boroaluminosilicate] (10)
k) steel wire (11)
l) continuous spun glass mat (12)
m) continuous spun glass yarn (13)
n) continuous spun glass fibers (14)
o) parallel wires on polyester mat (15)
p) GEVETEX [trademark of continuous fiber glass from Aachen Gerresheimer Textilglas GmbH] (16)
q) National standard etc (17)
r) silane (18)
s) brass sheath (19)

Fig.6 Comparison of the E-moduli of various fiber materials for the reinforcement of plastics (indicated maximum values, from the literature)

a) material Refer to p 9
E glass (1)
R glass (2)
S glass (3)
boron nitride fibers (4)
HM glass (5)
X glass (6)
fibers of stainless steel (7)
zirconium oxide fibers (8)
graphite fibers (9)
boron fibers (10)
HM carbon fibers (11)
silicon carbide fibers (12)
graphite whiskers (13)
saphire whiskers (14)

b) meaning of some abbreviations
boron aluminum silicate (electrical insulation fibers) (15)
magnesium aluminum silicate (16)
modified E glass (17)
aluminum silicate containing beryllium (18)
experimental spun glass, high strength (19)
high modulus filaments or fibers (20)
whisker= needle-like single crystal (21)

Fig. 7. Tensile strength as a function of fiber sample length according to [6] [(a) boron fibers (DFL, Stutgart), (b) American boron fibers, (c) E-glass fibers]. Refer to p 9.

Fig. 8. Strength of Wacker boron fibers after heat treatment (testing at ambient temperature. Refer to p 9.

Table 2. Strength properties of boron fiber composites. (1) Composite system; (2) % volume fiber; (3) Flexural strength; (4) E-Modulus; (5) Polyquinoxaline boron fibers; (6) Polyimide boron fibers; (7) Epoxy-boron fibers. Refer to p 10.

Table 3. Properties of boron fiber containing GFP. (1) Laminate structure; (2) Reinforcing material % vol.; (3) Resin; (4) Tensile strength; (5) E-Modulus in tension; (6) 95% static safety; (7) (Boron); (8) Glass mat; (9) .... Boron tungsten wire layers; (10) ------ Glass filament mat layers. Refer to p 10.

Fig. 9. Elastisity in tension (a) and compression (b) of plastics reinforced with boron fibers according to [5]. Refer to p 10.

Fig. 10. Comparison of tensile (a) and compression (b) of plastics reinforced with boron fibers according to [5]. Refer to p 10.

Fig. 11. E-Modulus in flexure and bending strength of boron fiber reinforced plastic as a function of support-to-thickness ratio l/d. (1) E-Modulus in pure bending stress; (2) Normal strength 5 in pure bending stress; (3) Shear stress at rupture; (4) Preponderantly shear rupture; (5) Transition zone; (6) Normal stress rupture zone. Refer to p 11.

Fig. 12. Possibilities of construction of stringer elements with boron fiber reinforced plastics (black). For connecting pieces advantageously glass or carbon reinforced plastic could be used. Refer to p 10.

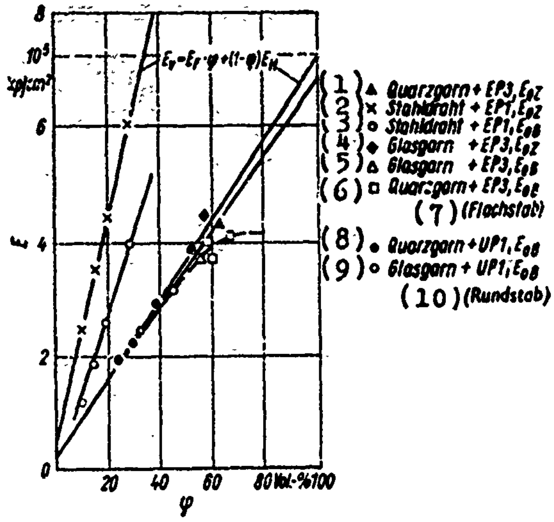


Fig. 1. E-modulus in flexure and tension, of unidirectionally reinforced laminates as a function of the fiber volume component.

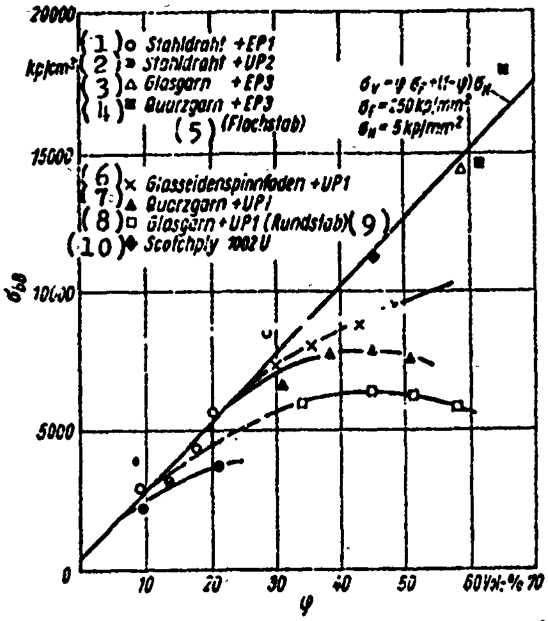


Fig. 2. Bending strength of unidirectionally reinforced laminates as a function of the fiber volume component.

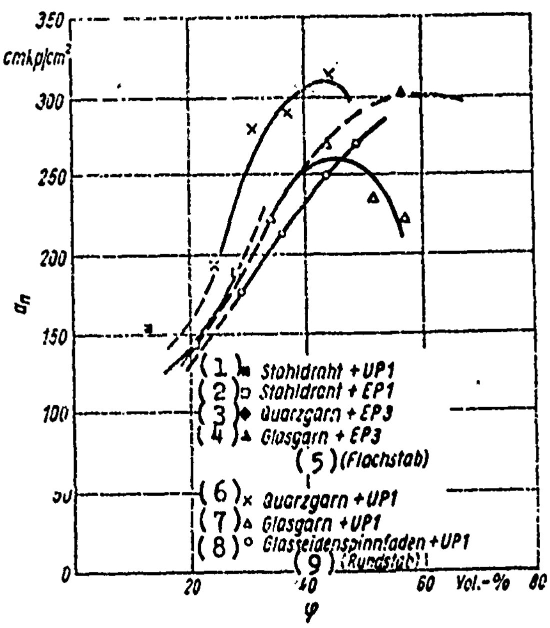


Fig. 3. Impact bending strength of unidirectionally reinforced laminates as a function of fiber volume component.

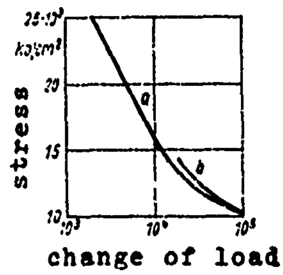


Fig. 4. Cycling stress (dry) in the case of steel wire laminates (a) and wires (b).

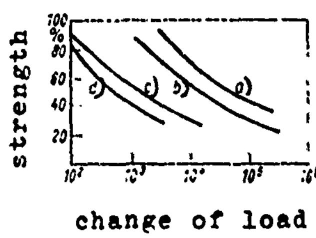


Fig. 5. Cycling stress of various materials [strength is indicated in % of short time strength: a) wire and wire laminated (dry), b) wire laminated (wet), c) GFP (dry), d) GFP (wet)].

(1) Verstärkungswerkst.	(2) Verstärkungsart	(3) Hersteller	(4) Faserdmr. [μm]	(5) Fadenfeinheit [tex]	(6) Dichte [g/cm³]	(7) Schlichte	(8) Faserfestigkeit [kp/mm²]	(9) Faser-E-Modul [kp/mm²]
(10) E-Glas	(12) Glasseidenmatte 216 S 219 BS	(16) GEVETEX Textilglas GmbH Düsseldorf	9	40	2,5	(18) Silan	[illegible]...300	7300
	(13) Glasseidengarn		9	68	2,5	GK 5	200...300	7300
	Glasseidenspinnfäden (14)		9	40	2,5	Silan (18)	200...400	7300
(11) Stahldraht	parallele Drähte auf Polyestervlies (15)	(17) National Standard Co. Ltd. Kidderminster	254	--	7,8	Messingummantelung (19)	250	21000

Table 1. Properties of steel wire in comparison to glass fibers.

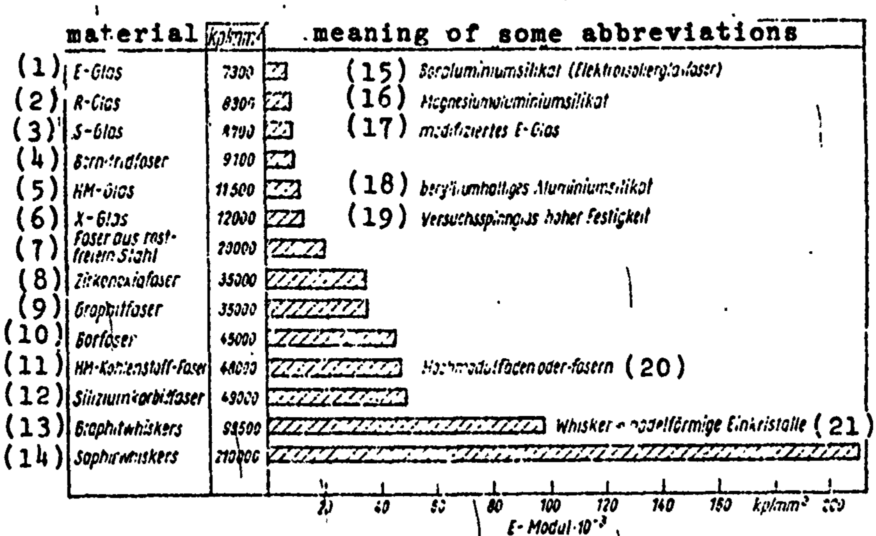


Fig. 6. Comparison of the E-moduli of various fiber materials for the reinforcement of plastics (indicated maximum values, from the literature).

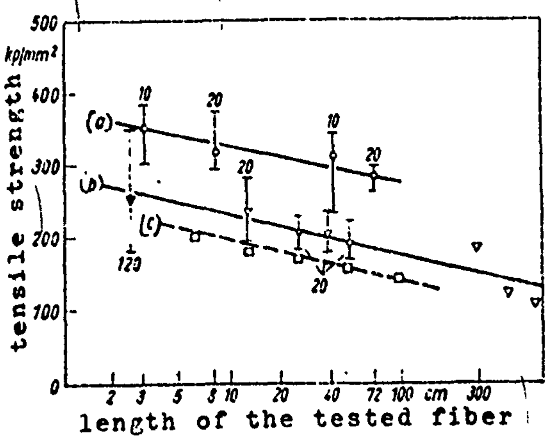


Fig. 7. Tensile strength as a function of fiber sample length according to [6] (a) boron fibers DFL Stuttgart), (b) American boron fibers, (c) E glass fibers].

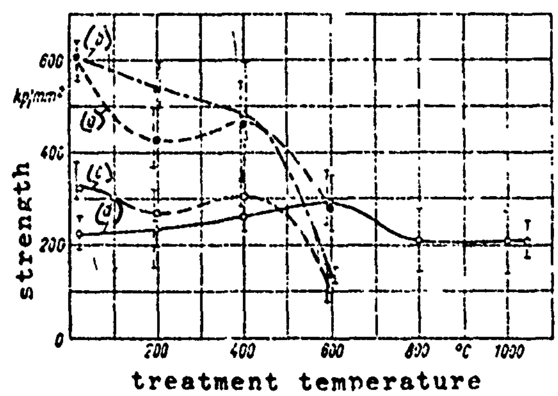


Fig. 8. Strength of Wacker boron fibers after heat treatment (testing at ambient temperature).

load type	treatment	year of mnfg.
(a) flexure	5 min in air	1968
(b) flexure	20 min in air	1968
(c) tension	20 min in air	1968
(d) tension	20 min in Argon	1967

(1) Verbundsystem	(2) Faden-Volumenanteil [%]	(3) Biegefestigkeit [kp/mm²]	(4) E-Modul [kp/mm²]
(5) Polychinoxalin Borfäden	60	176	25000
(6) Polyimid Borfäden	60	199	24000
(7) Epoxid-Borfäden	60	197	27750

Table 2. Strength properties of boron fiber composites.

(1) Laminataufbau	(2) Verstärkungswerkstoff [Vol.-%]	(3) Harz	(4) Zugfestigkeit [kp/cm²]	(5) Zug-E-Modul [kp/cm²]	(6) 95% statische Sicherheit [kp/cm²]
	(7) 18,5 (Bor)	EP	2700	$9{,}7 \cdot 10^{5}$	$\pm 1{,}7 \cdot 10^{5}$
	(8) 13 (Glasm.) (7) 12 (Bor)	EP	2200	$7{,}1 \cdot 10^{5}$	$\pm 1{,}1 \cdot 10^{5}$
	(8) 31 (Glasm.) (7) 5 (Bor)	EP	1850	$4{,}1 \cdot 10^{5}$	$\pm 0{,}3 \cdot 10^{5}$
	(8) 36 (Glasm.)	EP	1893	$1{,}5 \cdot 10^{5}$	–

(9) Bor-Wolfram-Draht-Lagen
(10) Glasseidenmattelagen

Table 3. Properties of boron fiber containing GFP.

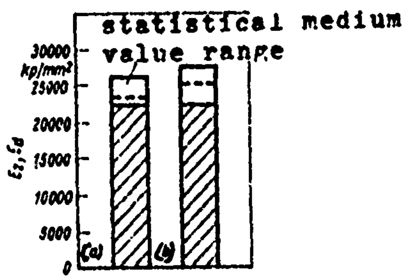
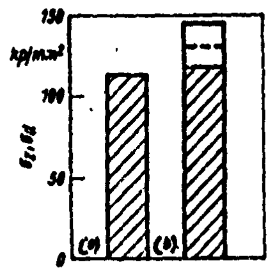


Fig. 9. Elasticity in tension (a) and compression (b) of plastics reinforced with boron fibers according to [5].



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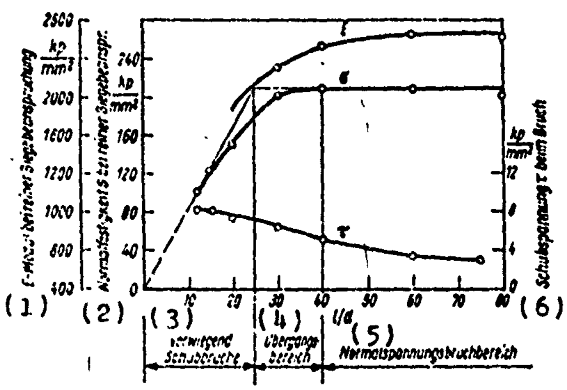

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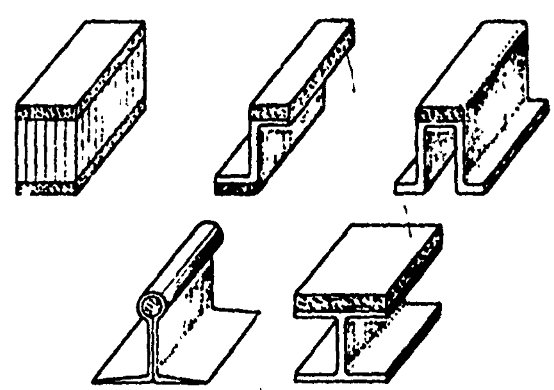

Fig. 12. Possibilities of construction of stringer elements with boron fiber reinforced plastics (black). For connecting pieces advantageously glass or carbon reinforced plastic could be used.